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PAPER

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The Alaska Wrangell Arc: ~30 Ma of subduction-related magmatism along a still active arc-transform junction

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Abstract

The Oligocene to Present Wrangell Volcanic Belt (WVB) extends for ~500 km across south-central Alaska (USA) into Canada at a volcanic arc-transform junction. Previously, geochemistry documented mantle wedge and slab-edge melting in <12 Ma WVB volcanic rocks; new geochemistry shows that the same processes characterized ~18–30 Ma WVB magmatism in Alaska. New $^{40}Ar/^{39}Ar$ ages demonstrate that WVB magmatism in Alaska initiated at ~30 Ma due to flat-slab subduction of the Yakutat microplate and that the dextral Totschunda fault was active at this time. Our results, together with prior studies, show that Alaskan WVB magmatism occurred chiefly due to subduction and should be considered a volcanic arc (e.g. the Wrangell Arc). The WVB provides a long-term geological record of subduction, strike-slip and magmatism. Slab-edge upwelling, flat-slab defocused fluid-flux and faults acting as magma conduits are likely responsible for the exceptionally large volcanoes and high eruption rates of the Wrangell Arc.

1 | INTRODUCTION

Along convergent margins, volcanic arc-transform junctions are common (Kamchatka, Park et al., 2002; Central America, Tibaldi, Pasquarè, & Tormey, 2010; etc.) and present a temporal record of both variations in the relative position of the leading front of the slab and translation of the upper plate along strike-slip faults (Portnagin et al., 2005). These slab-edge magmatic systems range from "typical" calcalkaline arc affinities to alkaline magmatism associated with upwelling asthenosphere along slab edges/slab windows and "leaky" strike-slip faults (e.g. Maury et al., 2004). In these settings, the geochemistry of erupted magmas depends in part on proximity to subduction-related mantle wedge melting, intra-arc extension, proximity to intra-arc strike-slip faults, variations in mantle source (e.g. subduction modified vs. unmodified) (Maury et al., 2004) and slab edges/windows (Thorkelson, Madsen, & Sluggett, 2011).

Flat-slab subduction occurs along ~10% of modern convergent margins (Gutscher, Maury, Eissen, & Bourdon, 2000) and is often associated with subduction of thick oceanic crust and broad zones of deformation (Gutscher, Spakman, Bijwaard, & Engdahl, 2000). There is no characteristic style of volcanism associated with flat-slab subduction. In central Mexico, there is an active continental arc ~800 km inboard of the trench that migrated ~100's km inboard during the Miocene (Ferrari, Orozco-Esquivel, Manea, & Manea, 2012), whereas in Peru, Miocene flat-slab subduction has led to the almost complete shutting off of arc magmatism (Bishop et al., 2017). Furthermore, flat-slab subduction adds a potential increased role for slab-edge melt as a contributor to the geochemistry of arc-transform systems (Portnyagin & Manea, 2008; Portnyagin et al., 2005), especially along transforms and slab windows (Yogodzinski et al., 2001).

The Oligocene to Present Wrangell Volcanic Belt (WVB) (Richter et al., 1990), Alaska (USA), provides a potentially exceptional long-term record (e.g. since its inception) of the geochemical and eruptive flux evolution of an arc-transform magmatic belt located along the corner of a subducting flat slab (Figure 1). The duration, petrogenesis and tectonic affinity of earliest WVB volcanism is unclear, owing mainly to the lack of studies from older volcanoes exposed in the spatial transition between <12 Ma WVB volcanoes (Preece & Hart, 2004; Trop, Hart, Snyder, & Idleman, 2012) and ~18–13 Ma volcanoes in adjacent parts of Canada (Figure 1) attributed to "leaky" transform magmatism (Skulski, Francis, & Ludden, 1992). Furthermore, recent geophysical imaging does not define a clearly imaged deep (e.g. >100 km) subducting slab under the WVB (Martin-Short, Allen, & Bastow, 2016), even though many large extinct, dormant and active volcanoes are present (Richter, Rosenkrans, & Steigerwald, 1995). These geophysical results, coupled with the aforementioned lack of geochronological/geochemical data across a significant portion of the central WVB, lead to a lack of clarity on the tectonic setting responsible for the WVB, and this is the focus of our study.

2 | BACKGROUND

The northern Pacific plate margin is characterized by a west-to-east transition from normal subduction to flat-slab subduction to transform tectonics (Haeussler, 2008). In the western region, subduction of the Pacific oceanic plate produces a well-defined trench, moderately dipping Benioff zone that reaches depths of 100–150 km within ~400 km of the trench and active volcanism in the Aleutian arc. The central region is distinguished by sparse active volcanism and a shallowly dipping Benioff zone produced by flat-slab subduction of thickened Eocene oceanic crust (e.g. oceanic plateau) referred to as the Yakutat microplate (Finzel, Trop, Ridgway, & Enkelmann, 2011). Presently subducting northwestward, the "flat" slab extends for ~250 km northwestward beneath Alaska at a subduction angle of ~6° before reaching a depth of 150 km more than 600 km inboard of the trench (Figure 1; Eberhart-Phillips et al., 2006).

The central WVB (Figure 1), the focus of our research, is adjacent to the Yukon and marked by active volcanism, shallow seismicity (< ~50 km; Stephens, Fogleman, Lahr, & Page, 1984) and right-lateral displacement along the Denali, Totschunda/Duke River and Fairweather faults (Benowitz et al., 2011; Haeussler, 2008; McAleer, Spotila, Enkelmann, & Berger, 2009). Limited geochronological data indicated that WVB magmatism initiated at ~26 Ma due to subduction of the Yakutat microplate (Richter et al., 1990). Geophysical analyses reveal a progressive west-to-east increase in the angle of subduction from 11° to 16° south of the WVB near the St. Elias Mountains and project the depth to the top of the subducting slab at ~80 km beneath the WVB (Bauer, Pavlis, & Landes, 2014).

The WVB extends >500 km across eastern Alaska, northwestern British Columbia and southwestern Yukon Territory, and includes

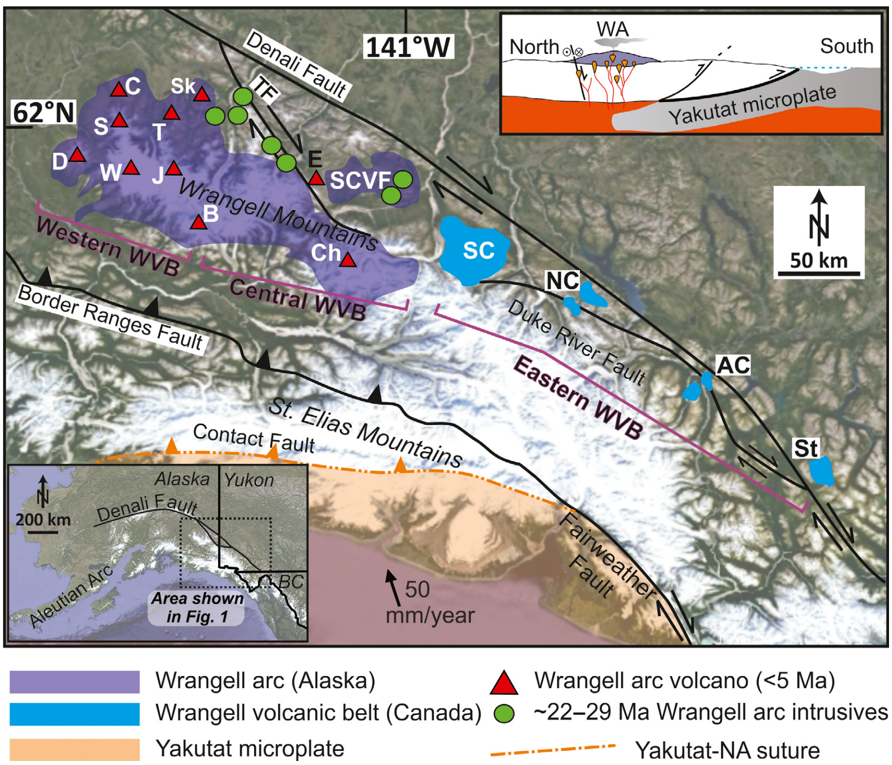

FIGURE 1 Map of southern Alaska and western Yukon, Canada depicting major tectonomagmatic features and central Wrangell volcanic belt (WVB) study area. TF, Totschunda fault. SCVF, ~18–30 Ma Sonya Creek volcanic field. <5 Ma Wrangell arc volcanoes: B, Mt. Blackburn; C, Capital Mountain; Ch, Mt. Churchill; D, Mt. Drum; J, Mt. Jarvis; S, Mt. Sanford; Sk, Skookum Creek volcanic centre; E, Euchre Mountain; T, Tanada Peak; W, Mt. Wrangell. Yukon volcanic fields: AC, Alsek; NC, Nines Creek; SC, St. Clare Creek; St, Stanley Creek. The St. Clare Creek volcanic field hosts lavas that have both arc and non-arc geochemical affinities (Skulski et al., 1992). Upper inset is cartoon cross-section depicting Yakutat microplate subduction and Wrangell arc magmatism, as well as strike-slip motion on the Totschunda Fault, after Richter et al. (1995). Based on the crustal thickness, velocity structure, shallow subduction angle and deformational response, the Yakutat microplate is interpreted as an oceanic plateau (Worthington et al., 2012). BC on lower left inset map is British Columbia, Canada. Yakutat plate velocity from Elliot, Larsen, Freymueller, and Motyka (2010) [Colour figure can be viewed at wileyonlinelibrary.com]

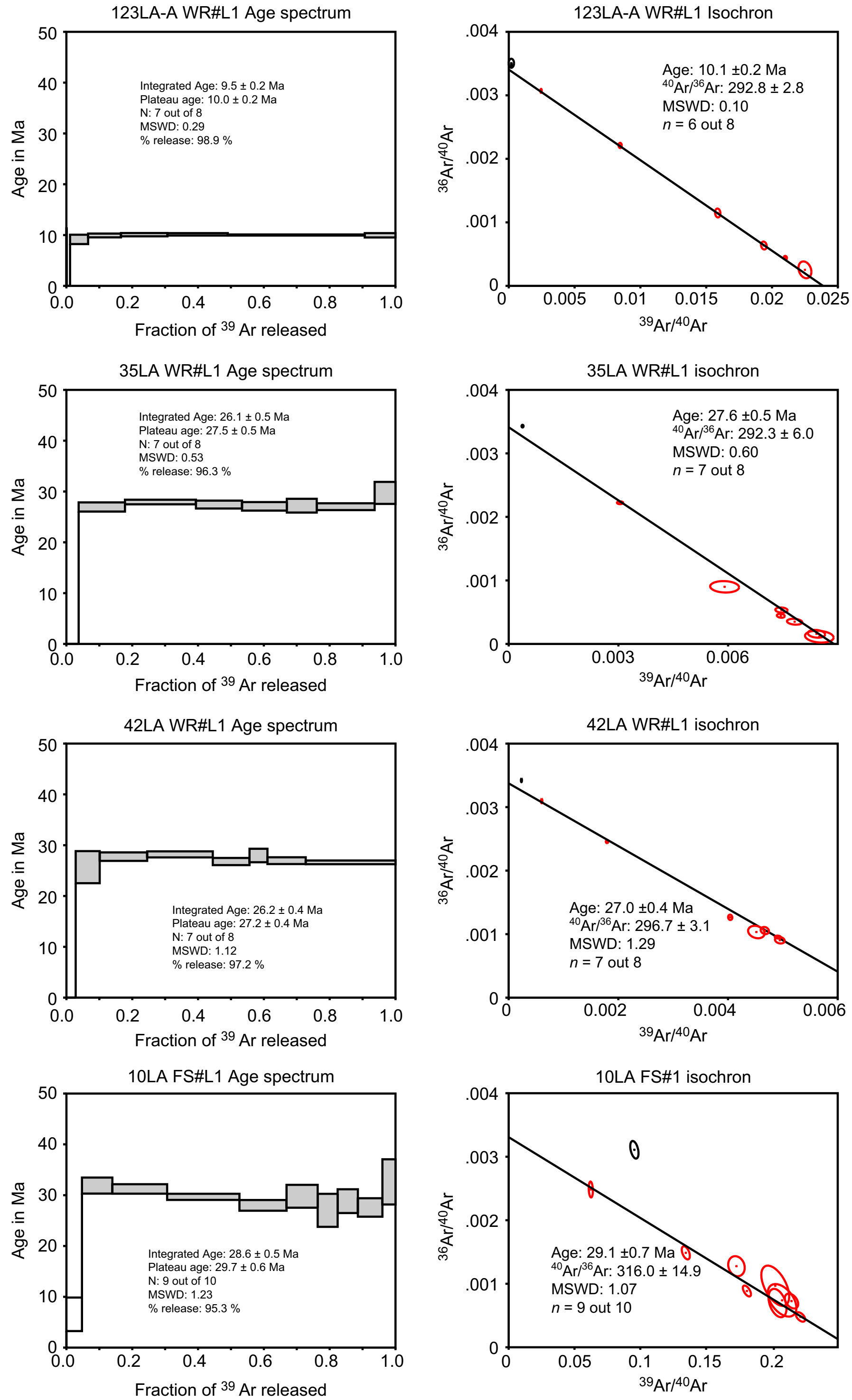

FIGURE 2 Four representative $^{40}Ar/^{39}Ar$ age spectra and isochron plots for newly dated samples in Alaska. Steps filled in grey were used for plateau age determinations. Steps filled in red were used for isochron age determinations. See Supporting Information Table DR1 for sample locations [Colour figure can be viewed at wileyonlinelibrary.com]

ice-capped Quaternary volcanoes, which are some of the tallest and largest continental volcanoes and largest andesitic shield volcanoes on Earth (e.g. Mts. Sanford, Wrangell, Churchill) (Richter et al., 1995). The physiographic volcanic arc component consists of elliptical volcanic fields populated with shield volcanoes and stratovolcanoes (Richter et al., 1995), which characterize other arc-transform junctions (e.g. Kamchatka, Park et al., 2002), as well as lavas, domes, pyroclastic deposits, calderas, cinder cones and volcaniclastic strata. Preece and Hart (2004) documented three geochemical types in <~5 Ma western WVB volcanic rocks: trend 1 calcalkaline to tholeiitic-transitional suite related to intra-arc extension; trend 2a calcalkaline suite that represents the largest volume of erupted magmas; trend 2b calcalkaline adakitic suite found only along the front-side of the active arc, formed by melting of the Yakutat slab.

In Canada, volumetrically smaller volcanic centres and strike-slip basins are concentrated along the >300-km-long Duke River

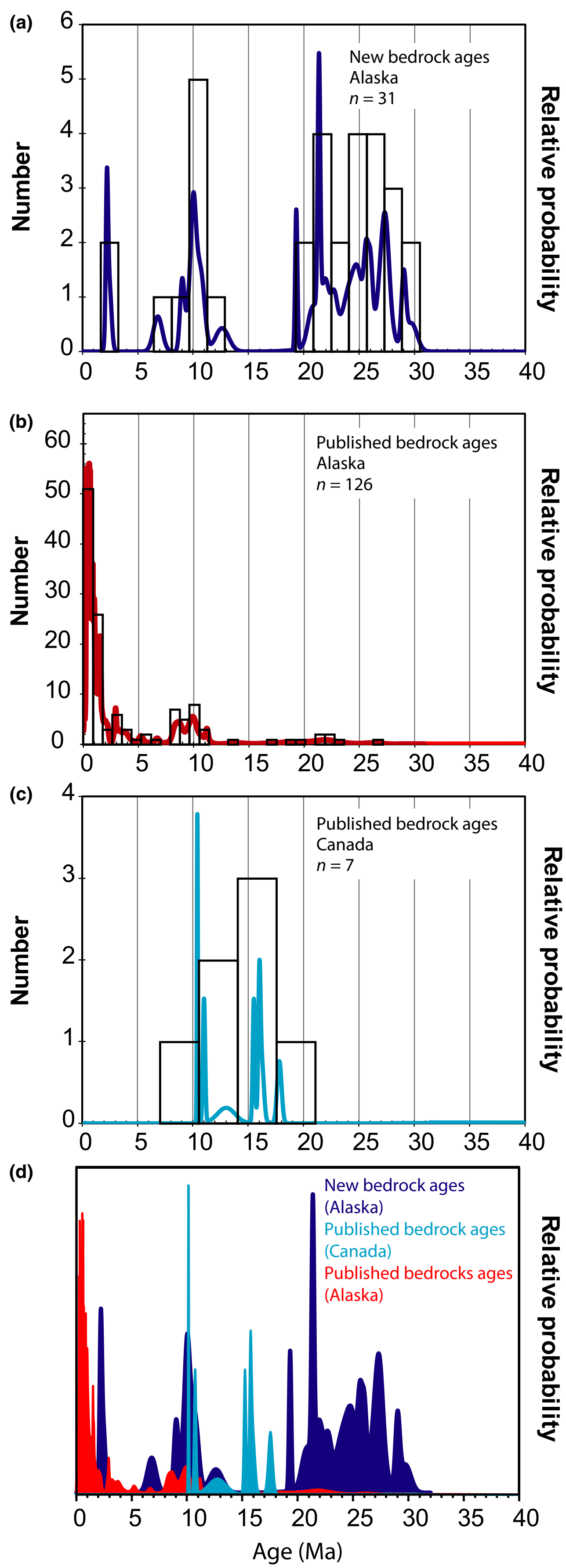

FIGURE 3 Probability Density Function plots of (a) new and (b) published ages from the Alaskan Wrangell arc and (c) Yukon Wrangell volcanic belt volcanic and plutonic rocks (e.g. lavas, tuffs, shallow intrusive rocks and plutons). See Supporting Information Table DR1 for data locations and references. (d) Summary plot showing data from A–C. Note the apparent gap in Alaska volcanism from ~18 to 13 Ma, as magmatism shifted southeast into Canada [Colour figure can be viewed at wileyonlinelibrary.com]

segment of the Denali fault system (Figure 1; Skulski et al., 1992). Less than 20 km east of the Alaska–Yukon border (St. Clare Creek; Figure 1), Skulski et al. (1992) documented geochemistries in >~16 Ma WVB lavas attributable to both strike-slip and subduction-related processes at the arc-transform junction. Alkaline magmas reflect asthenospheric mantle sources not affected by subduction that erupted along "leaky" strike-slip faults and transtensional basins, whereas magmas with transitional to calcalkaline chemistries resulted from an increased role of subduction-related arc magmatism and intraplate extension (Skulski et al., 1992).

3 | RESULTS AND DISCUSSION

3.1 | Age constraints on Wrangell Arc magmatism

Here, we present 30 new $^{40}Ar/^{39}Ar$ ages of WVB lavas, tuffs and intrusions and one dikelet sample intruding Totschunda fault gouge (Figures 2 and 3; Supporting Information Tables DR1 and DR2 in the Data Repository; refer to Data Repository for methods). These samples come from outcrops in the northern Wrangell Mountains, including the Sonya Creek volcanic field (Figure 1). The Sonya Creek volcanic field is critical in understanding WVB magmatism because it is where the earliest previously dated WVB rock originated (~26 Ma; Richter et al., 1990) and that age has been interpreted to represent the initiation of the WVB. Our new results range from 2.2 ± 0.1 to 29.7 ± 0.5 Ma (Figures 2 and 3; Supporting Information Table DR1). The ~18–30 Ma ages are all from samples in the Sonya Creek region or within ~90 km northwest (Figure 1). These include a ~29.7 Ma feldspar from a dikelet injected into fault gouge along the Totschunda fault, which we interpret to represent fluid flow at ~30 Ma into an existing and active fault zone. These new data demonstrate WVB magmatism initiated at least at ~30 Ma, several million years earlier than previously recognized, and show that ~18–30 Ma WVB magmatism extended across a region presently spanning ~100 km, larger than the ~20–35 km wide Sonya Creek volcanic field as formerly recognized (Richter et al., 1990).

3.2 | Geochemical constraints on Wrangell Arc magmatism

We present here 94 new bulk rock major and trace element analyses (Supporting Information Table DR3), which include 29 of the newly dated samples (all but the dikelet). These new data, combined with

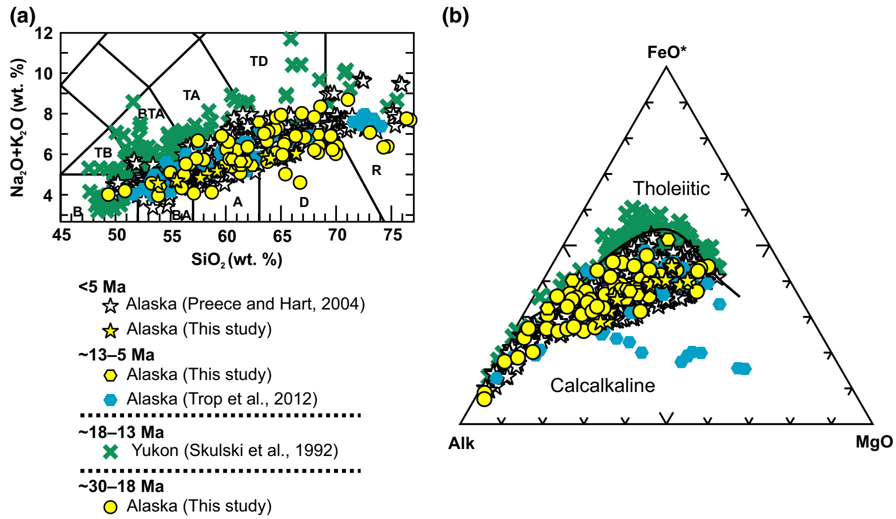

FIGURE 4 a, Volcanic rock classification of Wrangell arc (western and central Wrangell volcanic belt in Alaska) and Wrangell volcanic belt (eastern Wrangell volcanic belt in the Yukon) rocks from this study and prior work (Preece & Hart, 2004; Skulski et al., 1992; Trop et al., 2012) (Le Bas, Le Maitre, Streckeiser, & Zanettin, 1986). B: basalt; BA; basaltic andesite; A: andesite; D: dacite; R: rhyolite; TB: trachybasalt; BTA: basaltic trachyandesite; TA: trachyandesite; TD: trachydacite. Notice the higher alkali concentrations of Yukon rocks relative to Alaskan rocks. b, AFM diagram illustrating primarily calcalkaline nature of Alaskan rocks and more tholeiitic nature of Yukon rocks [Colour figure can be viewed at wileyonlinelibrary.com]

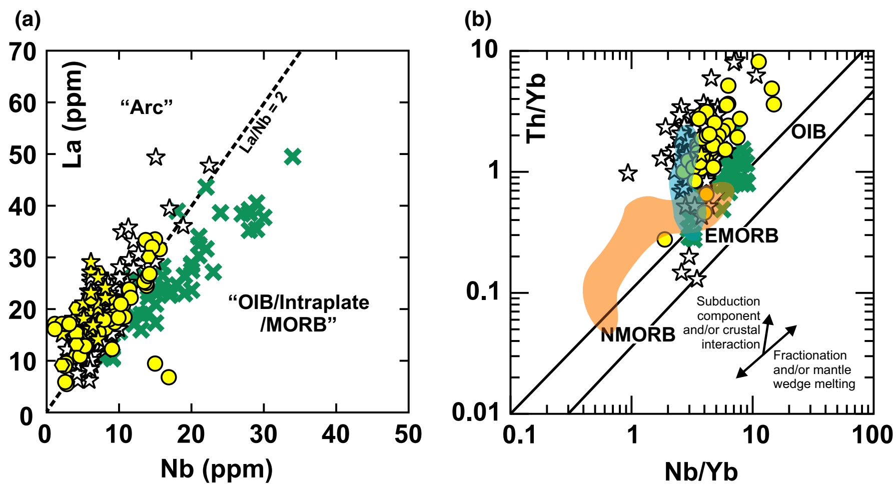

FIGURE 5 a, Nb vs. La. Alaskan samples plot primarily in the "arc" field, with higher La at a given Nb concentration, consistent with subduction enrichment. This diagram also shows the more intraplate character of the Yukon samples (e.g. more Nb-rich at a given La concentration). b, Nb/Yb vs. Th/Yb. Both Alaskan and Yukon samples fall on an array of increasing Th/Yb, with little to no increase in Nb/Yb. Light orange field is Wrangell Mountains region Triassic Nikolai Greenstone lavas (Greene, Scoates, & Weis, 2008) and light blue field is Cretaceous Chisana arc lavas (Barker et al., 1994). Both of these older units crop out among the sampled igneous rocks and represent possible crustal contaminants for WVB magmas. Legend as in Figure3 [Colour figure can be viewed at wileyonlinelibrary.com]

other published results, allow us to examine the geochemistry of WVB igneous products in the context of the entire duration of magmatism. Foundational in models of how volcanic arcs interact with major strike-slip faults is establishing that volcanism is truly due to subduction. Nye (1983), Preece and Hart (2004) and Trop et al. (2012) established that < ~12 Ma WVB volcanism in Alaska was arc-related; however, only a handful of geochemical samples are reported from the >12 Ma Alaska WVB (Richter, Ratté, Leeman, & Menzies, 2000), so its tectonic environment is ambiguous. Moreover, studies have implicated other processes for WVB volcanism such as slab windows (Thorkelson et al., 2011) and "leaky" transform faults (Skulski et al., 1992). Figure 4 illustrates the bulk major element chemistry of WVB bedrock samples, and all samples except the alkaline rocks from the Yukon overlap in space and are transitional to subalkaline, and calcalkaline (Figure 4). Figure 5 plots Nb vs. La and Nb/Yb vs. Th/Yb for WVB rocks. La enrichment and Nb depletion are characteristic of arc

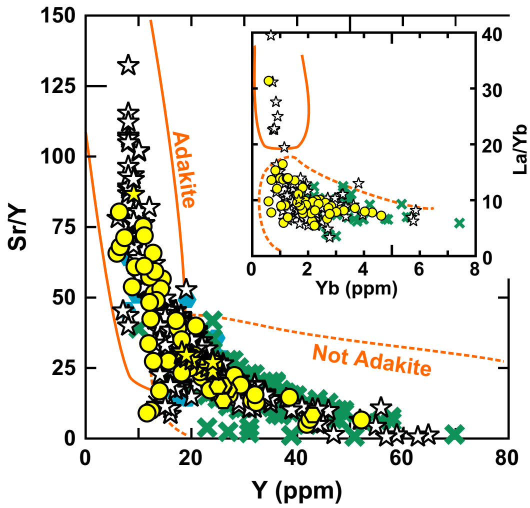

FIGURE 6 Sr/Y vs. Y and La/Yb vs. Yb. Solid orange line depicts adakite field, while dashed orange line depicts rocks that are "typical" calcalkaline mantle wedge melts, in subduction zones. The Alaskan samples with high Sr/Y and La/Yb are adakite-like and are interpreted as slab-edge melts (Preece & Hart, 2004; this study). Legend as in Figure3 [Colour figure can be viewed at wileyonlinelibrary.com]

magmas formed via melting of a subduction-affected mantle wedge (Pearce & Peate, 1995). Alaskan WVB lavas define a volcanic arc array in Figure 5a, while WVB samples from the Yukon have an intraplate geochemical signature. These same relations are illustrated in Figure 5b; Alaskan WVB rocks have Nb/Yb and Th/Yb values that mostly plot above the MORB–OIB array. Rocks that form via melting of a subduction-affected mantle wedge extend to higher Th/Yb depending on the degree of subduction enrichment. Th/Yb can also increase via interaction with continental crust; however, Th/Yb of local Wrangellia Terrane crust (e.g. Triassic Nikolai Greenstone and Cretaceous arc lavas) that WVB lavas could have interacted with cannot explain the range of Th/Yb displayed by WVB lavas (Figure 5b); interaction with Cretaceous crust could only cause some of the within-suite increase. Sr/Y vs. Y and La/Yb vs. Yb (Figure 6) illustrate the presence of adakite-like chemistries in the WVB eruptive sequence (e.g. <1 Ma rocks from Mt. Drum and Churchill; Preece & Hart, (2004), and newly collected ~18–30 Ma rocks from the central WVB, this study). We documented ~18–30 Ma adakite-like rocks only from the Sonya Creek volcanic field and similarly aged shallow intrusive rocks that crop out to the northwest (Figure 1). Overall, the chemical variations of WVB rocks are consistent with the hypothesis that Yukon WVB magmas formed via a different melting regime (e.g. slab window/intraplate and mantle source less affected by subduction; Thorkelson et al., 2011) than Alaskan WVB volcanism. The chemical characteristics of Alaskan WVB rocks, which indicate a subduction origin, also agree with their mineralogy (e.g. andesites dominated by amphiboles and two-pyroxene mineral assemblages).

In shallow-slab settings, defocused fluid-flux over a wide areal extent leads to low degree mantle wedge melting, as opposed to melting of a constricted mantle wedge in a "typical" subduction zone (Carr, Feigenson, & Bennett, 1990). This results in cumulatively large magma volume(s) (Carr et al., 1990; Kelley et al., 2010) and presumably large volcanoes. Furthermore, ample evidence exists that a deep (e.g. >100 km) depth to slab is not needed for mantle wedge melting and arc volcanism (England & Katz, 2010; Syracuse & Abers, 2006); thus, even though the WVB is underlain by the shallow-dipping Yakutat slab, mantle wedge melting can occur. Adakite-like chemistries have only been reported from Alaskan WVB samples; thus we agree with interpretations of Preece and Hart (2004) and Jadamec and Billen (2010) that WVB adakites represent slab-edge melting generated by mantle flow around and adjacent to the subducting Yakutat microplate. The leading corners of flat slabs are also conducive environments for long-lived arc magmatism due to the nature of the edge of an expansive planar surface and dip angle. Enhanced upwelling along the edge of the Yakutat slab, coupled with regional transtension associated with the major strike-slip faults that favours enhanced volcanism (e.g. Acocella & Funiciello, 2010), as well as the defocused fluid-flux over a shallow slab, likely accounts for the large size and volume of WVB volcanoes. The north–south orientation of normal faults among central WVB eruptive centres and intra-arc basins is consistent with transtensional deformation along the northwest-striking Totschunda-Fairweather fault system (Trop et al., 2012).

The Alaskan segment of the WVB represents a type of volcanic arc that may be under recognized in the geological record, namely one where the "classic" view of a volcanic arc formed by subduction forms a hundreds of kilometers long arcuate chain of potentially coeval volcanoes (Grove, Till, & Krawczynski, 2012). This difference, as well as the diversity of geochemical compositions erupted from large, hazardous WVB volcanoes, directly reflects the unique geodynamic setting in this part of North America, where subduction zone magmatism and mantle wedge melting occur in conjunction with dynamic shallow-slab subduction and upper plate translation along continental-scale strike-slip faults at an arc-transform junction. Similar arc-transform magmatic belts are likely present in the more deformed, deeper time record (e.g. Wang et al., 2009), but are not easily recognized without similar high-resolution sampling and geochemical/geochronological examination.

4 | CONCLUSIONS

Our results from unstudied, expansive >12 Ma volcanic outcrops in the central WVB, coupled with prior datasets and younger volcanic products examined during our study, and the spatial association of large, hazardous volcanoes above a geophysically imaged north-dipping shallow subducting slab, are best attributed to subduction-related processes and show that this part of Alaska has been affected by subduction-related magmatism for the last ~30 Ma, when the WVB initiated. The present study extends in time and space the conclusions of previous studies that <12 Ma WVB magmatism occurred chiefly due to subduction and indicates that the WA has been located at the leading edge of a flat slab since at least ~30 Ma. Stern (2016) defines arc magmatism as that which "occurs at straight or curved alignments of discrete volcano-plutonic complexes that form above a subduction zone, where oceanic material… is recycled into Earth's mantle." The entirety of the Alaskan side of the WVB fully satisfies these geological criteria and should be considered an arc, here named the Wrangell Arc (WA). We acknowledge there are volcanic products on the Canadian edge of the WVB that have arc affinity, which deserve further study.

New geochemical and geochronological data, coupled with prior studies, demonstrate that (a) continuous magmatism occurred throughout the ~30 Ma duration of the WA; (b) melting of a mantle wedge affected by slab-derived components led to arc volcanism in Alaska over this entire ~30 Ma duration, while mildly alkaline magmatism was focused in the Yukon from ~18 to 13 Ma; (c) fluid-flux from a shallow slab, slab-edge upwelling and transtensional deformation were likely responsible for the exceptionally large size and eruption rates of the WA; (d) the petrotectonic history of the WVB provides a framework to identify arc-transform magmatic belts in the geological record; (e) the leading corners of flat slabs are conducive environments for long-lived arc magmatism although the eruptive centres may be laterally shuffled by strike-slip faults.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure DR1. ^{40}Ar/^{39}Ar muscovite age spectra, Ca/K and Cl/K ratios for the new bedrock samples. Steps filled in grey were used for plateau and weighted average age determinations. Steps filled in red were used for isochron age determinations.

Table DR1. Compilation of new and recently published (Milde, 2014) bedrock ^{40}Ar/^{39}Ar Wrangell Arc ages.

Table DR2. Detailed whole rock and feldspar laser step heat data for ^{40}Ar/^{39}Ar geochronology.

Table DR3. Major and trace element geochemistry. Major elements reported raw in wt. % and trace elements in ppm.

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